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Citation for the original published paper (version of record):

Davidsson Kurland, S. (2020). Energy use for GWh-scale lithium-ion battery production.
Environmental Research Communications, 2(1). <http://dx.doi.org/10.1088/2515-7620/ab5e1e>

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To cite this article: Simon Davidsson Kurland 2020 *Environ. Res. Commun.* **2** 012001

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OPEN ACCESS

RECEIVED
30 September 2019REVISED
14 November 2019ACCEPTED FOR PUBLICATION
2 December 2019PUBLISHED
20 December 2019

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E-mail: simon.davidsson@chalmers.se**Keywords:** lithium-ion battery, energy use, life cycle assessment, LCA, energy analysis, battery manufacturing**Abstract**

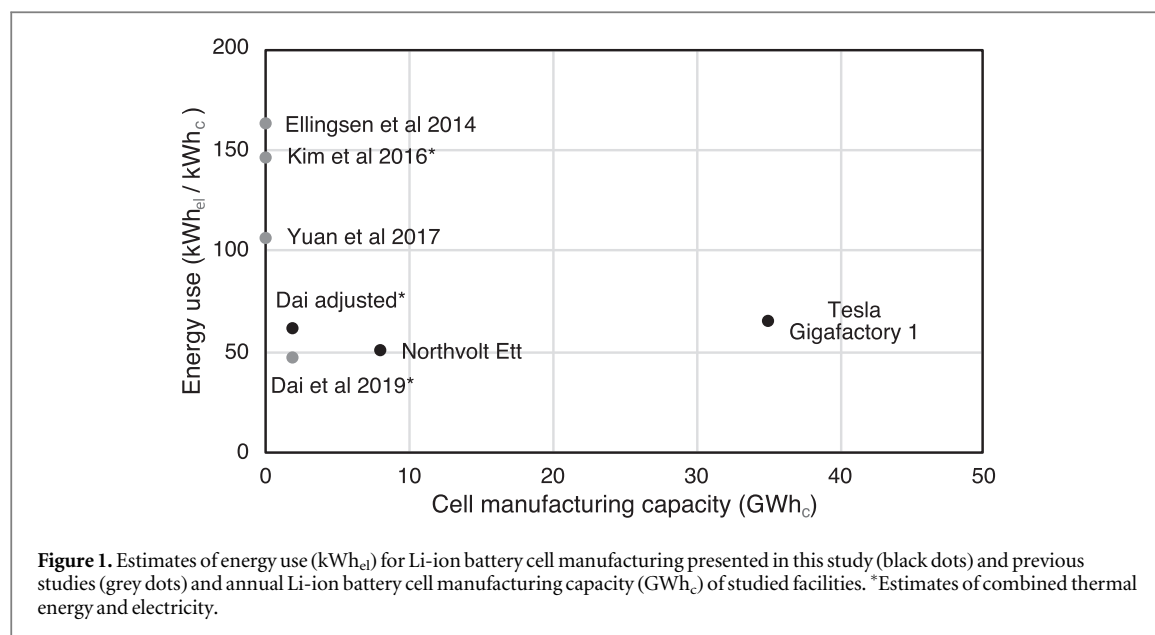
Estimates of energy use for lithium-ion (Li-ion) battery cell manufacturing show substantial variation, contributing to disagreements regarding the environmental benefits of large-scale deployment of electric mobility and other battery applications. Here, energy usage is estimated for two large-scale battery cell factories using publicly available data. It is concluded that these facilities use around 50–65 kWh (180–230 MJ) of electricity per kWh of battery capacity, not including other steps of the supply chain, such as mining and processing of materials. These estimates are lower than previous studies using data on pilot-scale or under-utilized facilities but are similar to recent estimates based on fully utilized, large-scale factories. The environmental impact of battery manufacturing varies with the amounts and form of energy used; especially as renewable sources replace electricity from fossil fuels. As additional large-scale battery factories are taken into use, more data should become available, and the reliance on outdated, unrepresentative, and often incomparable, estimates of energy usage in the emerging Li-ion battery industry should be avoided.

Introduction

Estimates of energy usage and greenhouse gas (GHG) emissions associated with producing lithium-ion (Li-ion) batteries have been shown to vary considerably (Ellingsen *et al* 2017, Peters *et al* 2017, Romare and Dahllöf 2017). Energy requirements related to the mining and processing of raw materials appear to be in reasonable agreement between studies (Dunn *et al* 2014), while energy used for module or pack assembly is considered to require only minimal amounts of energy (Dai *et al* 2019), leaving the cell manufacturing processes as the largest source for the variation. A significant portion of the discrepancy can be attributed to the fact that many estimates in the upper range are only valid for pilot-scale production or under-utilized industrial-scale facilities (Dai *et al* 2019). Others suggest that different methods lead to conflicting results (Ellingsen *et al* 2015). A greater understanding of the energy required to manufacture Li-ion battery cells is crucial for properly assessing the environmental implications of a rapidly increasing use of Li-ion batteries.

The environmental impacts of battery production tend to be quantified using life cycle assessment (LCA) using different impact assessment methods and assumptions for key aspects, making direct comparison of these studies difficult (Peters and Weil 2018). Also, conventional LCA studies might not be the correct tool for assessing the environmental impacts of emerging technologies (Arvidsson *et al* 2018). At least 20 Li-ion battery factories with an annual production volume of several gigawatt hours of Li-ion battery capacity (GWh_c) are currently being commissioned (IEA 2019). This has the potential of making more trustworthy data for the actual energy use from the manufacturing of battery cells available (Dai *et al* 2019). Still, few reliable estimates exist in the scientific literature, and studies still rely on average values of largely outdated data (Philippot *et al* 2019), or individual studies of pilot scale plants (Cox *et al* 2018).

Here, previously unpublished estimates of energy use for Li-ion battery cell manufacturing are presented. They are based on publicly available data of two multi-GWh capacity battery factories; the first from early company estimates, previously only available in technical reports written in Swedish and the other calculated from taxes paid on utilities. A comparison to previous estimates is made and further developments in assessing energy use and GHG emissions associated to Li-ion battery manufacturing is discussed.



Energy use for GWh-scale battery cell manufacturing

Northvolt Ett

Northvolt Ett is a battery cell factory under construction in Skellefteå, Sweden. It is intended to reach an annual production capacity of 32 GWh_c of Li-ion battery cells spread over four production lines (Northvolt 2018b). Construction of the first production line with an annual capacity of 8 GWh_c has started and plans for a second line are underway (Northvolt 2018a). The facility will perform most steps in the battery cell production from the preparation of cathode and anode materials to finished battery cells (Northvolt 2017b).

In a technical report appended to the Environmental Impact Assessment (EIA), the annual electricity consumption of the first 8 GWh_c production line is projected to be 400 GWh (Northvolt 2017b), equaling an electricity use of $50 \text{ kWh}_{\text{ei}}/\text{kWh}_c$ (figure 1). Electricity is likely to supply the absolute majority of the facility's energy demand since the most energy intensive processes, e.g. maintaining clean-rooms, heating ovens for the cathode production, and cell formation will use electricity, although there are also possibilities to use steam from a nearby combined heat and power plant or recycled heat from the production (Northvolt 2017b).

Tesla Gigafactory 1

Tesla Gigafactory 1 in Nevada, USA has a planned Li-ion battery cell production capacity of 35 GWh_c , with an additional 15 GWh_c of packs from cells manufactured elsewhere (Tesla 2014). Mass production of battery cells started in January 2017 (Tesla 2017). No official estimates of energy requirements for the factory have been made public, but Storey County is estimated to make an annual 1.4 million USD in utility franchise fees on electricity and natural gas from the facility (Applied Economics 2014). In 2017, Storey County made 992 000 USD from charging a 1% franchise fee on utilities from the Tesla project (GOED 2017). Since no natural gas is used in the Gigafactory (Tesla 2018), this revenue ought to come from the use of electricity.

Based on this, and the likely price paid for electricity, it is possible to calculate a crude estimate of electricity usage in the facility. A common electricity rate for large industrial customers in Nevada is 6.18 U.S. cents per kWh of electricity (Randazzo 2014). Assuming a 1% franchise fee, which is what was charged in 2017, a total annual electricity use of $2\,300 \text{ GWh}$ would be required to reach the estimated 1.4 million USD fees for the whole facility. This equals an energy use of $65 \text{ kWh}_{\text{ei}}/\text{kWh}_c$ (figure 1). Tesla's electricity is somewhat subsidized by the State of Nevada through an economic development rate rider (State of Nevada 2014). The discounted power price is valid up to 25 MW, starting at 30% for the first two years and declining with 10 percentage points every two years, reaching zero after 8 years. The average power demand correlating to an annual electricity consumption of $2\,300 \text{ GWh}$ is over 250 MW. This means that even if the rate rider affects the franchise fee, which is not evident, it would have only marginal impact on the result presented here.

With the Gigafactory, Tesla aims to vertically integrate as much of the supply-chain as possible, from raw materials to finished products, within the same facility (Fairley 2016). The main difference to the Northvolt Ett facility is that the Tesla Gigafactory 1 also assembles battery modules and packs. Since module and pack assembly tend to require only marginal energy demand compared to cell manufacturing processes (Dai *et al* 2019), the two facilities are comparable.

Comparisons to previous studies

Previous estimates of battery cell manufacturing energy use have utilized either bottom-up process modelling or top-down attribution of facility energy use, in either case rarely based on primary data (Ellingsen *et al* 2015). Estimates from studies relying on models, such as Notter *et al* (2010) and Dunn *et al* (2014), are lower than studies relying on primary data. In fact, the estimate from Dai *et al* (2019, 2017) has already replaced the data from Dunn *et al* (2014) in the widely used GREET model (Argonne National Laboratory 2018). Other well cited studies, such as Majeau-Bettez *et al* (2011) and Zackrisson *et al* (2010) are approaching a decade since publication, with even older secondary data used. The relevance of these estimates for modern multi GWh-capacity battery cell manufacturing plants should be questioned.

Several estimates of Li-ion battery manufacturing energy usage based on primary data do exist (figure 1). Dai *et al* (2019) estimate the energy use in battery manufacturing facilities in China with an annual manufacturing capacity of around 2 GWh_c to 170 MJ (47 kWh) per kWh_c, of which 140 MJ is used in the form of steam and 30 MJ as electricity. Ellingsen *et al* (2015) studied electricity use in a manufacturing facility over 18 months. Three different estimates were provided, with the lowest of 586 MJ (163 kWh) suggested to best reflect large-scale production (Ellingsen *et al* 2014). This estimate falls within reasonable proximity to more recent estimates, considering it is based on data from a fairly small manufacturing facility not running at full capacity. Yuan *et al* (2017) measured electricity use of a pilot-scale battery cell facility to 107 kWh.

In another example, Kim *et al* (2016) base their analysis on primary data from a battery cell manufacturing facility utilizing both electricity and steam, disclosed as 120 MJ of primary energy equivalents (PE-eq) per kg of battery (1500 MJ_{PE-eq}/kWh_c). The proportions of electricity and thermal energy, and how this is converted to PE-eq, is not disclosed. Dai *et al* (2019) approximates 1500 MJ_{PE-eq}/kWh_c to equal 525 MJ_{el}/kWh_c, using a primary energy conversion rate of 0.35, although it was previously estimated as 990 MJ/kWh_{PE-eq}, with 2/3 coming from steam and the rest electricity (Dai *et al* 2017).

Despite using two completely different methods, the two new estimates presented here are similar at 50 and 65 kWh_{el}/kWh_c. Also, although not based on primary data, especially the lower estimate are very similar to the 47 kWh proposed by Dai *et al* (2019). Thermal and electrical energy are not perfect substitutes, but Dai *et al* (2019) do sum up thermal energy with electricity. Although some processes require electricity, a large share of the energy required for Li-ion battery manufacturing are used in the form of heat at different temperatures, which can be supplied by either steam, hot water, or electricity (Northvolt 2017b). To avoid confusion, when possible, the actual requirements of thermal and electrical energy should be accounted for.

While the estimate from Dai *et al* (2019, 2017) is mainly based on primary data from battery cell manufacturing facilities, the electricity use for cell formation and charging is based on a quite simplistic calculation and estimated to 1.2 kWh_{el}/kWh_c. Northvolt expects to use as much as 20% of the total electricity consumption, equaling 15 kWh_{el}/kWh_c, for cell formation, despite the aim to reuse a large portion of the electricity (Northvolt 2017b). Using the higher Northvolt estimate for instead of the calculated number provides an adjusted estimate of Dai *et al* (2017, 2019) at just over 60 kWh_{el}/kWh_c (figure 1).

Moving forward

Understanding the energy requirements in the rapidly growing Li-ion battery industry is important, not only to accurately estimate the environmental impact, but also to assess the implications for the local power grids. For instance, the estimated annual electricity consumption of 2 TWh for Northvolt Ett equals roughly half of the power generated by the local municipal power company (Israelsson 2017). The plant is planned to run continuously every hour of the day and every day of the week (Northvolt 2018a). This new continuous demand of power could potentially decrease the regulating capacity of the hydropower in the area and have other effects on the potential for renewables in Sweden. Such impacts should be further investigated.

Keeping track of which different energy carriers and sources that are used becomes increasingly important with increasing shares of renewable energy in electricity systems. Tesla Gigafactory 1 utilize only electricity and aims at getting all electricity from renewable sources in the future (Tesla 2018) and Northvolt Ett will rely on clean electricity from wind and hydroelectric power in Sweden (Northvolt 2017a). The potential for switching to low-carbon energy sources is not as certain in those facilities currently relying on steam from fossil fuels, such as those studied in Dai *et al* (2019).

Based on public data on two different Li-ion battery manufacturing facilities, and adjusted results from a previous study, the most reasonable assumptions for the energy usage for manufacturing Li-ion battery cells appears to be 50–65 kWh of electricity per kWh of battery capacity. These results are considerably lower than many previous studies of smaller or under-utilized facilities. However, no further decrease in energy usage can

be seen when increasing the size of the facilities above 2 GWh_c, but further work is needed to confirm this. When better data becomes available, please discard the estimates presented here.

Acknowledgments

The author would like to thank Daniel Johansson and other members of the Mistra Carbon Exit project for numerous valuable discussions, two anonymous reviewers for excellent comments on the original manuscript, and Sara Kurland for proofreading.

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